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Failure Simulation Testing of the Z-1 Spacesuit Titanium Bearing Assemblies

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The Z-2 is a candidate for NASA's next generation spacesuit, designed for a range of possible missions with enhanced mobility for spacewalks both on planetary surfaces and in microgravity. Increased mobility was accomplished through innovations in shoulder and hip joints, using a number of new bearings to allow spacesuit wearers to dip, walk, and bend with ease; all important tasks for a planetary explorer collecting samples or traveling over rough terrain. The Advanced Spacesuit Development Team of NASA Johnson Space Center requested that the NASA White Sands Test Facility (WSTF) perform a series failure simulation tests on three titanium bearing assemblies, an elemental part of the joint construction used in new spacesuit designs. This testing simulated two undetected failures within the bearings and as a result the objective of this test program was to evaluate whether a failed or failing bearing could result in ignition of the titanium race material due to friction. The first failure was an inner seal leak sufficient to pressurize the race with +99 percent oxygen. The second failure was an improperly installed or mismatched ball port that created a protrusion in the ball bearing race, partially obstructing the nominal rolling path of each ball bearing. When the spacesuit bearings are assembled, bearing balls are loaded into the assembly via a ball port. The ball port is specific and unique to each bearing assembly (matched pair). The simulated mismatched ball port is a significant source of friction, which would be caused by an assembly error. To evaluate this risk, the bearings were cycled in a simulated worst-case scenario environment, with operational loads, and potential flaw conditions. During test the amount of actuation torque required and heat generated through continuous operation were measured and the bearings were observed for sparks or burning events. This paper provides detailed descriptions of the test hardware, methodology, and results.

Nomenclature

~ = approximately
DC = direct current

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DTO	=	Development Test Objective
EVA	=	extravehicular activity
h	=	hours
in-lb	=	inch-pounds
JSC	=	Johnson Space Center
kPa	=	kilopascal
min	=	minutes
mm	=	millimeters
N·m	=	Newton-meter
O ₂	=	oxygen
psi	=	pound per square inch
psig	=	pounds per square inch gauge
Ti	=	titanium
WSTF	=	White Sands Test Facility

I. Introduction

The Advanced Spacesuit Development Team of NASA Johnson Space Center (JSC) requested that NASA White Sands Test Facility (WSTF) perform a simulation test on three titanium bearing assemblies, an elemental part of the joint construction used in the Z-1 spacesuit. Bearings from the prototype Z-1 spacesuit were tested in support of the development of the new Z-2 spacesuit. The Z-2 is a candidate for NASA's next generation spacesuit, designed for a range of possible missions with enhanced mobility for spacewalks both on planetary surfaces and in microgravity. Increased mobility was accomplished through innovations in shoulder and hip joints using a number of new bearings to allow spacesuit wearers to dip, walk, and bend with ease; all important tasks for a planetary explorer collecting samples or traveling over rough terrain. This prototype system (Figure 1) is to be tested in planetary and micro-gravity test environments to feed design decisions for an upcoming space station Development Test Objective (DTO) suit development project. Engineers want to use titanium for the bearing materials in the spacesuit because of the material's high strength-to-density ratio. With a goal to reduce overall suit mass, titanium is a much lighter material; however, the spacesuit has high oxygen concentrations and titanium is one of the easiest materials to ignite in oxygen. Once ignited, titanium will burn in sub-atmospheric pressures of less than 1 psi (6.89 kPa)¹. There are various material properties that contribute to titanium's ease of ignition; however, if those can be overcome, the engineering benefits are well worth it.

II. Background

A series of tests were conducted in the late 1990s to evaluate the flammability risk of using titanium bearings.^{2,3} The titanium bearing assembly materials had burned in atmospheres similar to those in the spacesuit, so there was a concern that failure of one or more ball bearings could result in friction-induced ignition. Each of the tests were conducted at various pressures, rotational speeds, and operational durations under the assumption that the worst-case failure was a seized steel ball within the bearing race that would result in direct frictional sliding of steel on titanium. The first four test phases were executed using steel pins with a spherical end sliding around a titanium gothic arch. Each of the phases resulted in the generation of sparks, a sign that ignition could occur. The fifth phase of testing involved increasing the fidelity by spinning an actual titanium wrist bearing in which two balls had been pinned together to simulate a fused ball bearing, a more "real world" scenario. This phase did not result in any sparking or signs of ignition after 736 cycles, or the equivalent of two 8-h extravehicular activities (EVAs) of cycling. Despite the successful wrist bearing test the titanium wrist bearing was not flown.



Figure 1. Z-2 Space Suit

III. Test Objective

The objective of this test program was to evaluate whether a damaged or failing bearing could result in ignition of the titanium race material due to friction. To evaluate this risk, the bearings were cycled in a simulated worst-case environment, with operational loads, and anticipated flaw conditions. The operational loads were comprised of plug and manned loads. Plug loads being those loads induced into the bearings by pressure within the suit and manned loads being those induced by the wearer of the suit. Specifically, the manned loads are the amount of load that a human can put into the suit without any externally induced sources. The values for these loads used in the testing were derived from previous testing done on the current Extravehicular Mobility Unit (EMU)⁴. During test the amount of actuation torque required and heat generated through continuous operation were measured and the bearings were monitored for sparks or ignition events. The specific test profiles for each bearing are discussed in Section V.

IV. Test Plan Overview

This testing simulated two simultaneous undetected failures, each within the bearings.⁵ The first failure was an inner seal leak sufficient to pressurize the race with +99 percent oxygen. The second failure was an improperly installed or mismatched ball port that created a protrusion in the ball bearing race, partially obstructing the nominal rolling path of each ball bearing. When the spacesuit bearings are assembled, bearing balls are loaded into the assembly via a ball port. The ball port is specific and unique to each bearing assembly (matched pair). The simulated mismatched ball port is a significant source of friction that would be caused by an assembly error.

The first phase of testing was conducted for 96 hours (h) of cycle time. The cycle rate, speed, and simulated loads were based on previous manned suit testing.⁴ The second phase of testing was conducted immediately following the 96-h test and involved an increased load on each bearing for 30 minutes (min). All testing was conducted in an atmosphere of 12.4 psia (85.5 kPa), 99 percent (or better) gaseous oxygen. This pressure was a conservative value and due to a lower pressure limitation of the flammability test chamber at WSTF.

V. Test Hardware Description

A. Titanium Bearing Assemblies

Three titanium bearing assemblies representing the hip bearing, the scye (shoulder) bearing, and the waist bearing were tested. Each of the bearings' ring and race elements were fabricated using titanium alloy Ti-6AL-4V, the same alloy used in the bearing materials from the previous tests conducted in the 1990s. As a comparison these early tests did not utilize actual bearings for most of these tests but rather a gothic arch with a sliding pin assembly to simulate non-rolling ball bearings. Cross sections for each bearing assembly used in the tests described in this paper are shown in Figures 2 through 4. Note that while the figures show the lip and environmental seals, the actual bearing assemblies tested did not have them installed. This simulated a compromised seal(s) and the whole assembly was placed in the enriched oxygen environment during test.

The ball bearings were in an alternating configuration between 440C stainless steel balls and Vespel® balls to reduce friction. The balls and race were lubricated with Braycote® 814Z during use and would be protected from external particulate by two environmental seals. However, environmental seals and lip seals were removed for this test series to simulate the worst-case seal leak. All three bearings were of similar construction, each using identical materials, with dimensional variations to accommodate the unique load case based on the anatomical placement of the bearings in the suit. All bearings tested have been used for manned suit testing in atmospheric conditions.⁶ Prior to test the bearings were cleaned, lubricated, and the condition of the bearings documented.

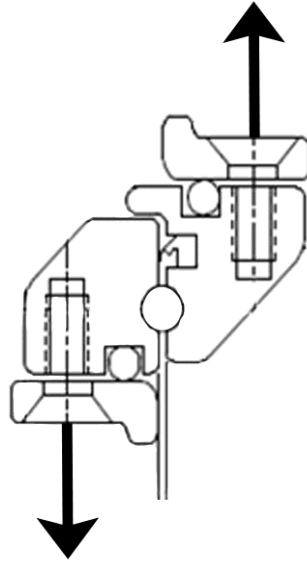


Figure 2. Hip Bearing Cross Section with Load Indication Arrows

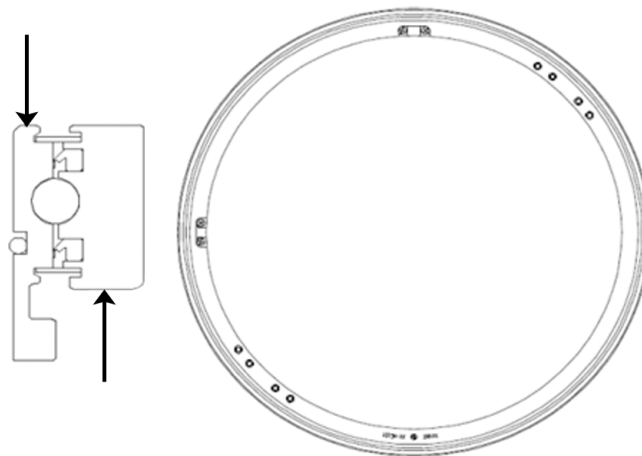


Figure 3. Scye Bearing Cross Section with Load Indication Arrows

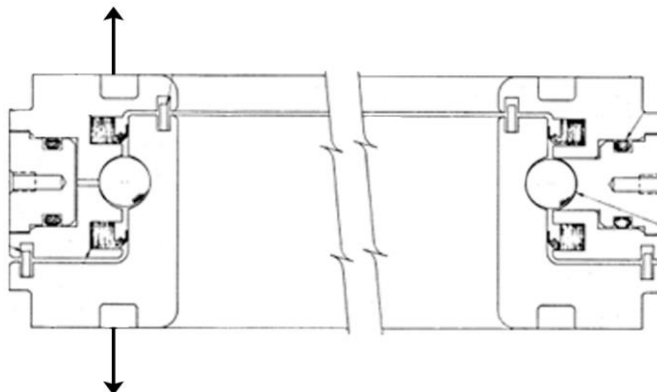


Figure 4. Waist Bearing Cross Section with Load Indication Arrows

B. Test Parameters and Approach

The load applied to the three bearings were a summation between the plug load and manload. During the design of the testing it was agreed that the manloads would be limited and held constant. They would also be based on the EMU manload models that were used during its development⁴. In Phase II of the testing the pressure load component was increased from 60.7 kPa to 70.1kPa simulating a failed suit pressure regulator. The atmospheric pressure in which the bearings were being tested was held constant at 85.5 kPa and was the result of a low pressure limitation of the flammability test chamber. The original intent was to test at the same pressure conditions as the simulated suit pressures but because of the limitation the pressure was agreed upon and as well it represented a conservative pressure and thus a conservative test with respect to oxygen flammability of the materials.

These loads were applied to the titanium bearing assemblies while rotating. All reaction forces, angular velocities, relative positions, chamber pressure, and inner bearing race temperatures were recorded via digital data acquisition. The bearings were rotated over a set angular displacement and then returned to the original position. One forward and back movement constituted a single cycle. A five Omega type K thermocouple array was placed on the inner race to measure temperature fluctuations (within 2.2°C which is the accuracy of the thermocouples), centered on the ball port (source of flaw), with spacing dictated by range of rotation.

The number of cycles for the bearings were chosen from operating extreme perspectives. It is expected that the arms in a suit would be used the most (and have the highest arc length) in a micro-gravity environment. Therefore, the number of cycles on the scye bearing were based on the EMU cycle model. Hip and waist cycles were based off of expected extreme walking based cycle models expected in planetary type activities astronauts may perform.

In addition to digital data acquisition, video was used to visually document all tests and capture any visible sparks emanating from the bearing races. The chamber was darkened to allow for enhanced spark detection. During testing, the console (video and data) was monitored at all times by the test team. Any visual observance of substantial sparking coming from the bearing or a mechanical failure of the bearing would have resulted in a test stoppage. Due to the construction of the waist assembly, visual verification of sparks was difficult. A posttest inspection was conducted to detect signs of ignition indicated by any discoloration of the alloy by oxidation. These would appear as bluish or varied colored marks or spots in the metal from the different oxidations states of titanium as a direct result of heat. The test profiles are listed in Table 1.

Table 1. Test Profiles

Test Article	Max Velocity (deg/s)	Max Arc (deg)	Cycles	Bearing Diameter		Pressure		Media O ₂	Load ^a	
				(in.)	(mm)	(psia)	(kPa)		(lb)	(kg)
Hip	78	45	96 h of 20/min - 1 h 40/min - 45 min 52/min - 30 min	11.74	298.19	12.4	85.5	+99%	1111	504
			Phase II: 30 min @ 52/min						1305	592
			96 h @ 20/h						720	326.6
Seye	135	135	Phase II: 30 min @ 20/h	9.21	233.93	12.4	85.5	+99%	850.2	385.6
			96 h of 20/min - 1 h 40/min - 45 min 52/min - 30 min						1983	899.4
Waist	52	30	Phase II: 30 min @ 52/min	15.53	394.46	12.4	85.5	+99%	2324	1054
			96 h of 20/min - 1 h 40/min - 45 min 52/min - 30 min						1983	899.4

^a Sum of plug loads @ 8.8 psia (60.7 kPa) and manned loads.

C. Test System

A test apparatus was developed to rotate the bearing while simultaneously applying the tensile load. An electric, brushless, direct current (DC) stepper motor was used to rotate one race of the test bearing assembly; the other race of the bearing assembly attached to the load cell plate located above the bearing assembly. A pneumatic cylinder was used to apply a tensile load normal to the bearing assembly plane of rotation. The pressure was supplied to the cylinder by a nitrogen k-bottle connected to a regulator. The load was applied through a pivot arm attached to the cylinder; the pivot lifts a ball end rod attached directly to the Omega LCHD-4K load cell. The load cell was mounted to a plate that attaches to the inner or outer race of the bearing assembly. The GSE 2220 torque transducer was coupled to the motor on one side and flanged shaft on the other. A mounting plate attached the bearing assembly to the flanged shaft. Five thermocouples, mounted on the inner diameter of the bearings, provided temperature data. By the design of the test, the load applied to the test articles could not exceed 150 ± 20 percent of the maximum test load. To prevent overload, a nitrogen bottle with the pressure equivalent to exert 150 percent maximum load with the air cylinder and linkage was used for each test. Three fixture configurations were used for this test to simulate load cases specific to each bearing assembly.

The test apparatus was installed in the 287 ft³ (8.1 m³) flammability chamber located in the WSTF oxygen test area (Figure 5). The chamber was filled with +99 percent oxygen, at 12.4 psia (85.5 kPa), as the test atmosphere.

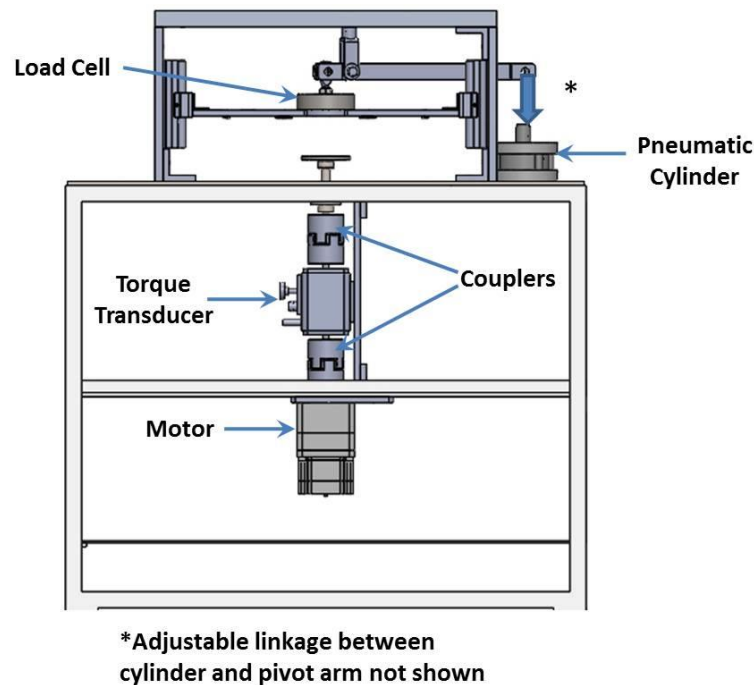


Figure 5. Test Apparatus

D. Hip Configuration

The hip bearing was mounted to a plate to distribute the load evenly across the entire brief side of the bearing and from two points 180 degrees apart (utilizing three screws per side) on the leg side of the bearing. The load path for the bearing when installed in the suit is across all screws fairly equally on the brief side of the bearing, but through only the axial brackets on the hip side. This best simulates the end use configuration of the bearing. Insulators were installed between the bearing and test fixture to slow thermal soak to the test apparatus. The inner race was rotated in this configuration. The hip bearing fixture is shown in Figures 6 and 7.

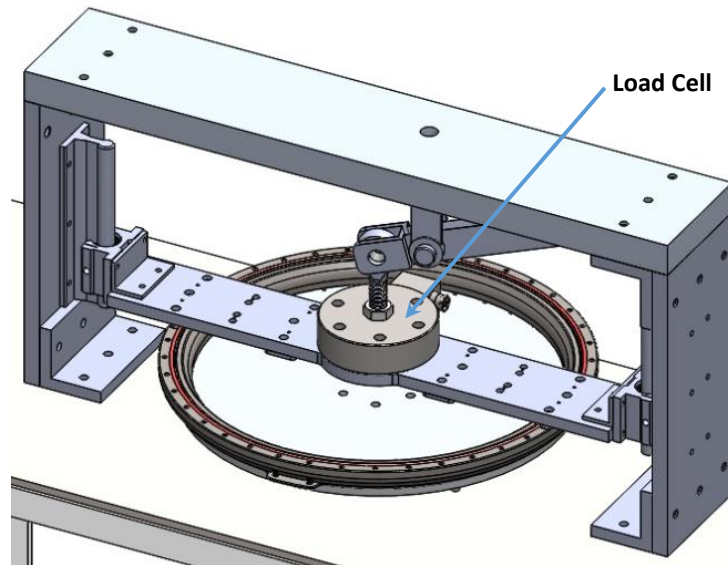


Figure 6. Hip Test Configuration

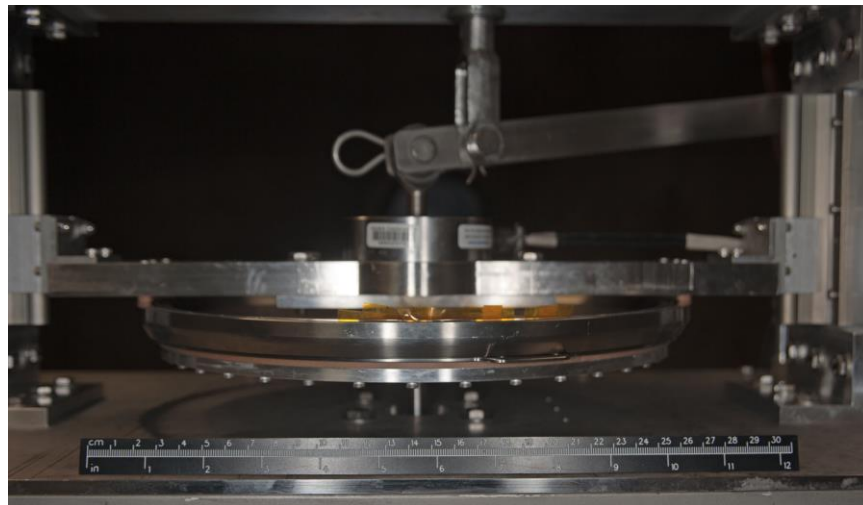


Figure 7. Hip Posttest Photo

E. Scye Configuration

The scye bearing used a detailed mounting configuration at specified locations to better simulate actual load conditions applied by the spacesuit. The configuration also needed to place the bearing inside a “scye carrier” which contacts the bearing on its shoulder (where upper load arrow is shown in figure 3) and is held in place by pressure when installed in the actual suit. Thus, the loading directions are different than those in the hip and waist bearings. This also allowed for adequate attachment points to the test apparatus while being robust enough to sustain the test-specified thrust load. The inner race was attached to a stationary load plate via two spacers 180 degrees apart. The outer race was rotated in this configuration and is held via scye carrier and attached by four brackets spaced 90 degrees apart. Insulators were installed between the bearing and the fixture to slow thermal soak to the test apparatus. A diagram of this test setup is shown in Figure 8. Figure 9 shows the pretest installation.

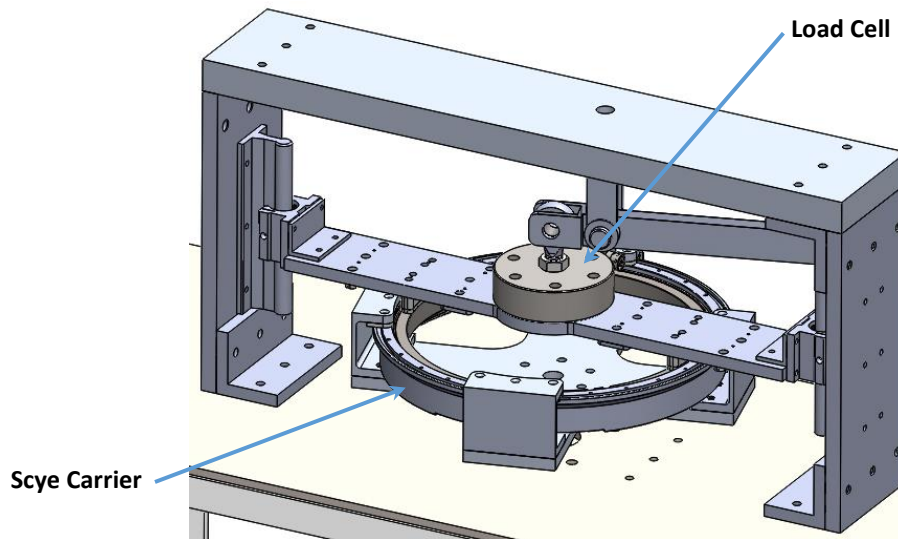


Figure 8. Scye Test Configuration

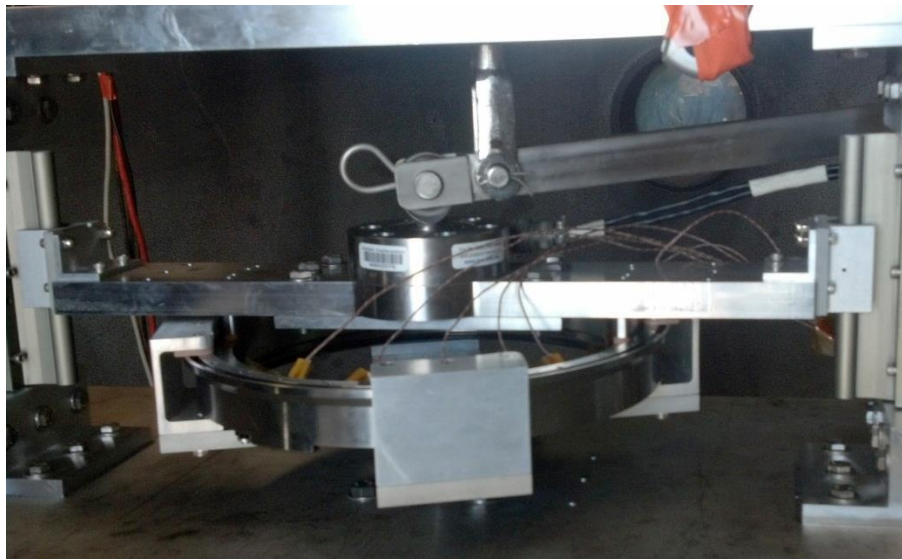


Figure 9. Scye Test Pretest Installation

F. Waist Configuration

The waist bearing was mounted to plates to distribute the load evenly across both sides of the bearing. When the bearing is installed in an actual suit this load case is consistent with the load path in the suit as the bearing is expected to be bolted to a hard upper torso and sizing elements below it. Insulators were installed between the bearing and test fixture to slow thermal soak to the test apparatus. Figure 10 shows the waist bearing test configuration.

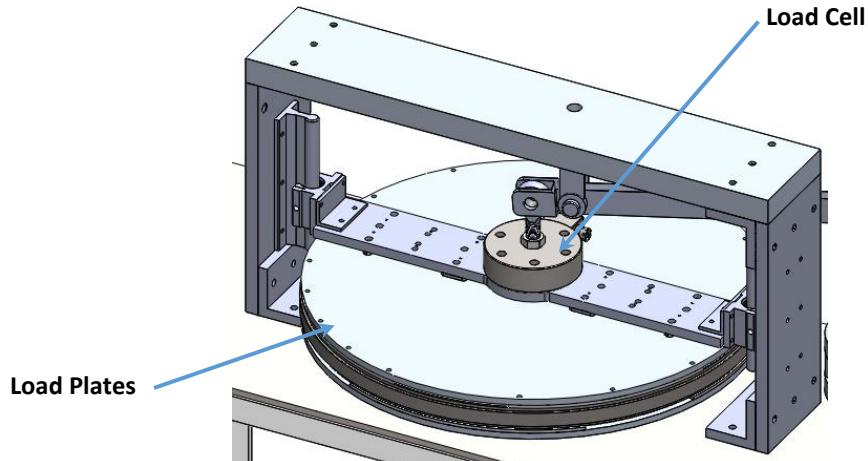


Figure 10. Waist Test Configuration

VI. Results and Discussion

A. Hip Bearing

No visual indications of sparking occurred over the 96-h (193,920 cycles) test duration; however, the bearing's actuation torque increased significantly and decreasing of the mechanical performance was observed. An audible "ratcheting" sound was noted by the test team near conclusion of the test, and rotational resistance was observed. The initial torque reading was 50 inch-pounds (in-lb) (5.649 Newton-meters (N·m)) and remained steady until ~45 h, then began to increase. The final torque reading was ~200 in-lb (22.59 N·m) for Phase I. Maximum bearing/ambient temperature differences of up to ~12 °F (6.7 °C) were observed and the bearing temperature remained above ambient temperature throughout the entire test. Phase II ran immediately following Phase I testing. Torque readings resumed at about 200 in-lb (22.59 N·m) for Phase II. Posttest inspection revealed debris on the fixture table resulting from the frictional wear of the bearings (Figure 11). Raw data plots for hip bearing Phases I and II are in Figure 12.



Figure 11. Debris on Table Posttest

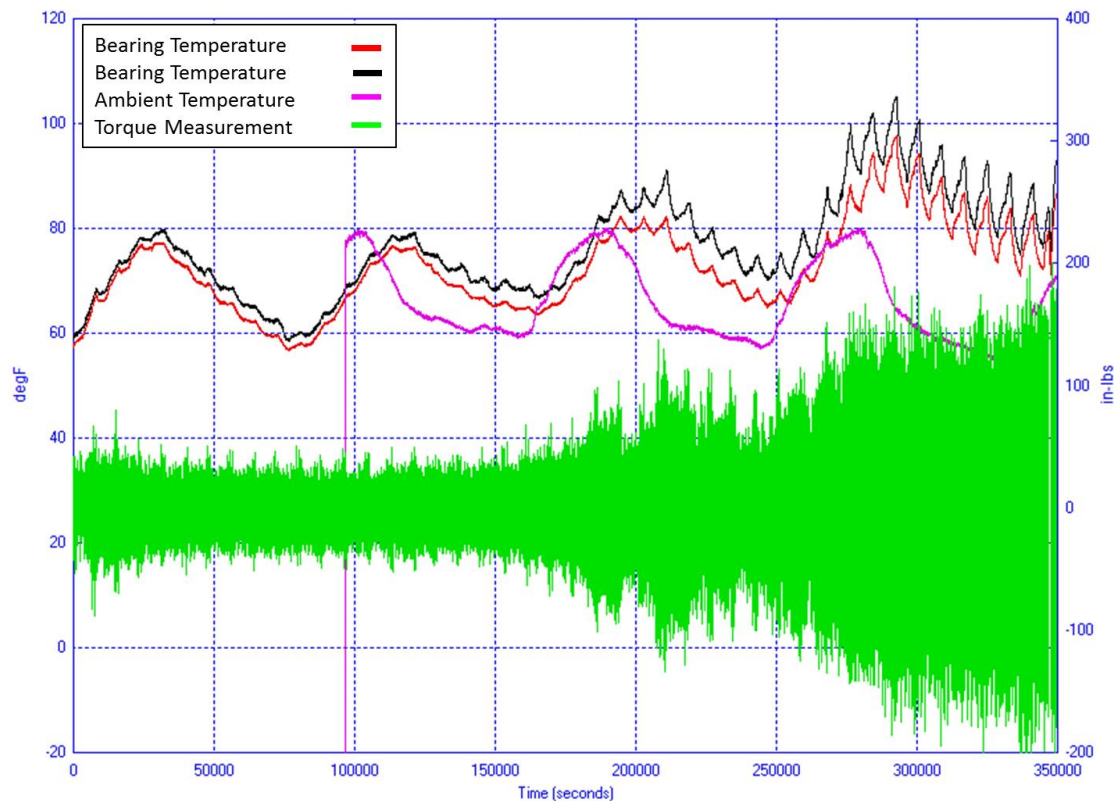


Figure 12. Hip Bearing Phase I and II

B. Scye Bearing

No visual indications of sparking, in the form of burning metal particulate ejecta, occurred over the 96-h (1920 cycles) test duration. Phase II was performed immediately following Phase I testing. Temperature increases were not significant and remained steady throughout the test. Torque readings, however, were found to be inconsistent (Figure 13). The torque data exhibited hysteresis during the 3-min pauses between cycles and held the last value measured instead of returning to zero as expected. It was also suspected that the sample rate was not fast enough to fully characterize the 135 degrees/second rotation event. Posttest the torque transducer was removed and calibration was validated. The results revealed the torque transducer was operating correctly and no significant change in performance was noted when compared to the previous calibration. One possibility for the torque anomaly could be that when the bearing was loaded into the test fixture a slight axial load was applied through the torque transducer, which skewed the resting torque reading. This was determined to be a reasonable scenario after review of the installed bearing and test fixture interfaces. Special care would be taken in subsequent tests to load the bearing before couplers were tightened.

Due to the abrupt stop and change in direction during cycling, a mechanical ringing sound was observed and oscillations were recorded in the torque data. No debris was present on the test fixture table posttest.

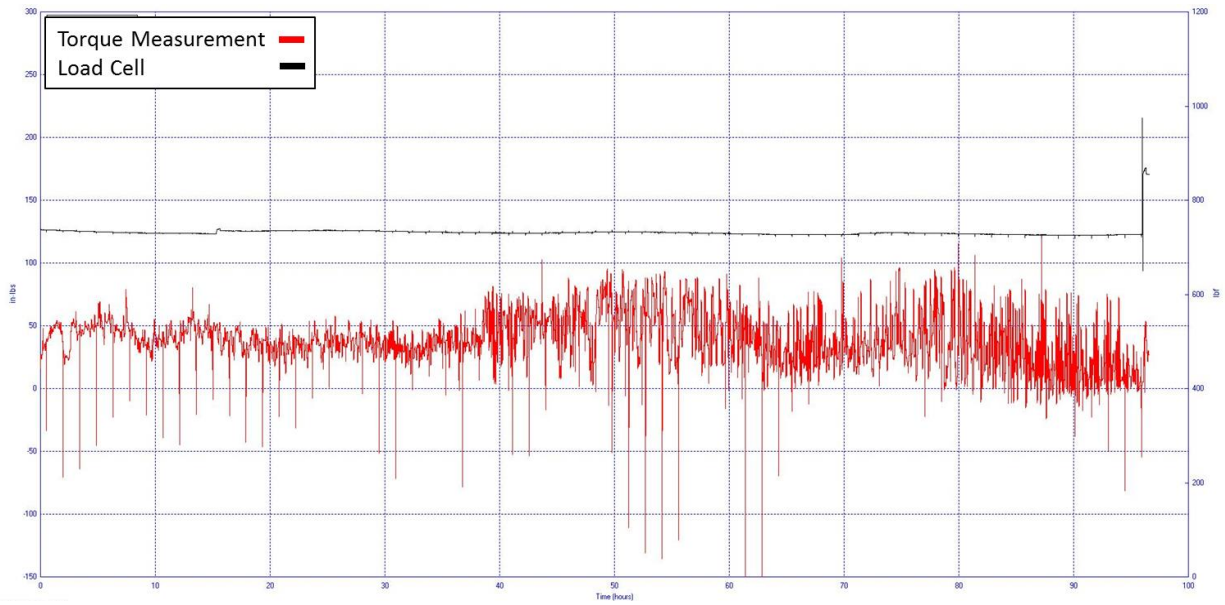


Figure 13. Scye Bearing Phase I and II

C. Waist Bearing

Due to the configuration of the test bearing design (unlike the scye and hip), the bearing balls are not visible; however, video of the outer race was still observed during the test with no indication of spark being observed over the 96-h (193,920 cycles) test duration. An increase in torque was observed over the duration of the test.

Initial torque reading was between 60 to 70 in-lb (6.78 to 7.91 N·m) while running the 20-cycles/min and 40-cycles/min profiles. While running the 52 cycle/min profile, the measured torque was around 100 in-lb (11.3 N·m). The torque values remained consistent throughout the test. Phase II ran immediately following Phase I testing and torque values measured around 90 in-lb (10.16 N·m). No debris indicating mechanical breakdown due to friction was found posttest. Raw data plots for waist bearing Phases I and II can be seen in Figure 14.

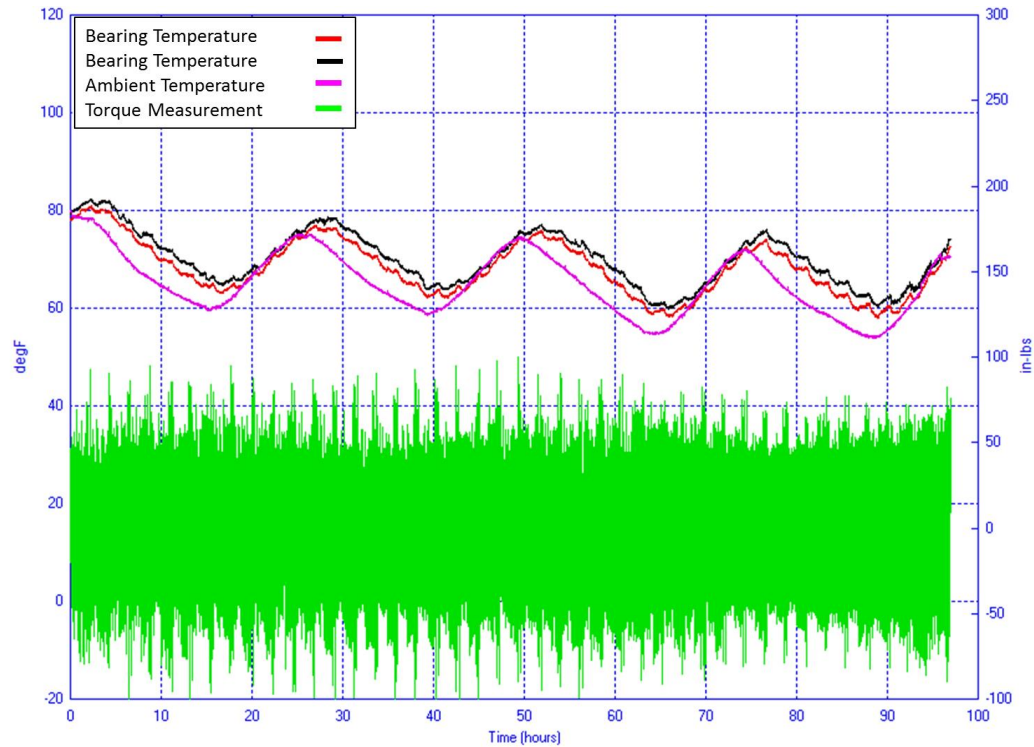


Figure 14. Waist Bearing Phase I and II

D. Follow-on Testing

Additional testing was requested to be performed on a hip bearing assembly to further investigate the mechanical wear of the bearing witnessed in the previous test and the effect of maintenance on the performance of the bearing. This test was conducted under the same load conditions and duration as Phase I testing; however, the chamber door was open to ambient atmosphere (~12.4 psia (85.5 kPa), ~20.9 percent oxygen) because an enriched oxygen atmosphere and the flammability aspect of the bearing race material was now not the subject of study.

The test article was configured with the inner environmental lip seal installed between the races. This test was not actively monitored, but was checked periodically. A torque cutoff limit of 110 in-lb (12.43 N·m) was added to the test program to ensure the bearing was not cycled under excessive torque. The parameters of this test were similar to previous testing with the addition of a pause at 48 h to service the bearing. Service to the bearing was executed per internal requirements including: complete disassembly, photographs, cleaning, reassembly and lubrication. The bearing was then reinstalled in the fixture and testing resumed.

At the onset of testing there was a steady increase in torque. The initial torque reading was 48 in-lb (5.42 N·m); around 3 h the torque leveled off and remained ~85 in-lb (9.60 N·m). The bearing was cycled for 48 h and never reached the 110 in-lb (12.43 N·m) torque limit. At this point, the bearing was disassembled, cleaned, and reassembled as a simulated maintenance.

The bearing was reinstalled in the fixture, the load applied, and testing resumed. Initial torque was measured at ~31 in-lb (3.50 N·m). The torque steadily increased until the cutoff limit of 110 in-lb (12.43 N·m) was reached, 1.8 h into testing. The test system paused when the torque limit was reached, and the test article system was checked with no apparent anomalies in the test system and testing resumed. After ~5 min the torque limit was reached again and the test paused. Upon reaching the torque limit or even continuing with an increasing torque in the bearing during operation it was decided by the test engineers to evaluate what might ultimately happen to a bearing while being cycled beyond what a reasonable astronaut would do in a suit. There upon the test team initiated a final restart to confirm the torque value would prohibit further testing per the requested torque limits. It was confirmed that the torque limit was reached during cycling of the 52 cycles/second profile. After completing ~5.75 h of run time, the test was stopped. After the massive amounts of wear and debris seen in the hip, it was suspected that the bearing lubricant was drying out and the buildup of worn ball bearing debris was then becoming a contributing factor to the overall bearing wear. The hope was that if cleaning and relubrication was conducted after 24 h that it would alleviate

some of the wear and tear. It is now believed that the ball bearing wear was more of a contact stress problem more than anything else, and this follow-on test helped determine why the ball bearings were exhibiting this unexpected wear.

VII. Conclusion

Testing performed in the 1990s showed titanium in the tested configuration was difficult to ignite, if at all, in the extreme test conditions used. The testing done in this series is of a different bearing design and the understanding of how to safely use previously unacceptable materials (like titanium) has matured from 20 years ago. The testing in this series was much more refined than the previous tests and more in line with the way the bearings would be used and or might fail.

The objective of this testing was to evaluate whether a damaged or failing bearing could result in an ignition of the titanium race material due to friction. To evaluate this risk, the bearings were cycled in a simulated worst-case scenario environment, with operational loads, and potential flaw conditions. The operational loads were comprised of calculated plug and manned loads. During test the amount of actuation torque required and heat generated through continuous operation were measured and the bearings were observed for ignition events. Signs of ignition would include the visual observation of an emitted burning particle of metal (spark), a darkened discoloration of the titanium alloy (oxidation), or an obvious loss or consumption of the materials (burning). None of the bearings tested exhibited any of these signs of ignition upon posttest bearing disassembly and inspection. Although torque increases were measured in all bearings tested, temperature increases due to friction were observed to be negligible. The test results demonstrated that the use of titanium in this specific application is worth pursuing in further maturing the bearing and suit design.

Acknowledgments

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